Modulation of Coulomb Blockade Behavior of Room Temperature Operational Single Electron Transistors by Tunnel Junction

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Abstract—The effect of tunneling oxide thickness on the Coulomb blockade behavior of a room temperature operating multi dot Single Electron Transistors (SET) was investigated. Our room temperature operational SETs, fabricated from focused ion beam deposited tungsten nano-islands, clearly show the modulation of Coulomb Blockade voltage with the change in the tunnel oxide thickness. The Coulomb blockade voltage of the device was increased from 2.0 V to 5.0 V by the reduction of tunnel junction thickness from 9 nm to 3 nm. In the present experiment, a decrease in the thickness of the tunneling oxide resulted in an increase in the conductance and tunnel current of the device by two orders of magnitude. The total capacitance of the SET device was reduced from 0.7 atto F to 0.5 atto F with the reduction in the thickness of the tunnel junction thickness of the SET. The charging energy of the SET device was increased from 110 meV to 146 meV with the reduction of the tunnel junction thickness from 9 nm to 3 nm, the modulation of the Coulomb blockade voltage was achieved with the variation in the tunnel junction thickness of the SET device.

***Index Terms*—Single Electron Transistors, Focused Ion Beam, Tungsten nanoparticles, Coulomb blockade, Tunnel junction, Charging energy.**

I. Introduction

Single Electron transistors (SET) are one of the possible solutions for the next generation nano electronic devices. SET devices are believed to be one of the the potential devices which would be used as future building blocks for the nano-scaled electronic devices, in the application areas like high density memory and nano sensing [1─2]. Tunnel junctions with very small capacitance are vital for the operation of these devices. The current conduction through the SET is controlled by the quantum mechanical tunneling of the electrons through the tunnel barrier. The SET devices consist of a central conducting island connected to the source and drain terminals via the tunnel junctions, and are capacitively coupled to the gate electrode. The tunnel junctions of the SET are characterized by the tunnel resistance and tunnel capacitance. When the electronic devices are scaled down to few nano meters, the energy levels in the conducting island become discrete due to the confinement of electrons to the nano-scaled island [3]. The high tunnel resistance of the tunnel junctions confines the electrons on the central conducting island. Coulomb blockade is observed in these nano-scaled devices. Coulomb blockade is the phenomenon where the electron tunneling is opposed until the applied source drain voltage is greater that the threshold voltage. The threshold depends on the total capacitance of the SET device. The Coulomb blockade voltage can be modulated by changing the total capacitance of the device, which depends on the capacitance of the conducting island, the capacitance of the tunnel junctions and the gate capacitance.

Fabrication of room temperature operating Single Electron Transistors (SETs) is a formidable challenge, because of the difficulties in production of uniform sub 10nm structures for charge transport [4─5]. Recently, we demonstrated successful fabrication of W-nano-island based room temperature operational SETs using Focused Ion Beam (FIB) deposition technologies [6]. The SET device fabricated using FIB deposition technology was a multi dot based device. In the present paper, the modulation in the Coulomb blockade voltage for a room temperature operating multi dot SET device is achieved by the variation in the tunnel junction properties of the SET. The changes in the Coulomb blockade voltage and other device parameters with the variations in the tunnel junction thickness was investigated. The reduction in the tunnel junction thickness resulted in the decrease of tunnel resistance and increase in the differential conductance of the SET device. The increase in the Coulomb blockade voltage of the SET device was achieved by the reduction of the tunnel junction thickness of the SET, resulting in the reduction of the total capacitance of the device increasing the charging energy of the device.

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II. EXPERIMENT

The SET devices were fabricated on an Al_2O_3 thin film, which was deposited on a silicon substrate using a Perkin Elmer 2400−8J parallel plate RF sputtering system. The deposited Al_2O_3 thin film was 300nm thick. This Al_2O_3 layer acts as an isolating layer between the device and the substrate. The deposition of conducting nano-islands on the passivating layer was achieved using a Hitachi FB-2000A focused ion beam (FIB) system. Tungsten nano-islands were deposited in a random arrangement over the 16μm × 16μm area. The average sizes of the deposited nano-islands were 10 nm in diameter, with the average spacing of 4 nm between the nano-islands. After the deposition of the nano-islands the nano and micro scaled electrodes and the probing pads for the device were fabricated using the FIB deposition process. The nano-scaled electrodes with a length of 50μm and a width of 250nm were deposited using the FIB deposition process. The probing pads having the dimensions of 100μm × 100μm were also fabricated using FIB deposition, the top view of the fabricated SET device is shown in the SEM micrograph in Fig. 1.

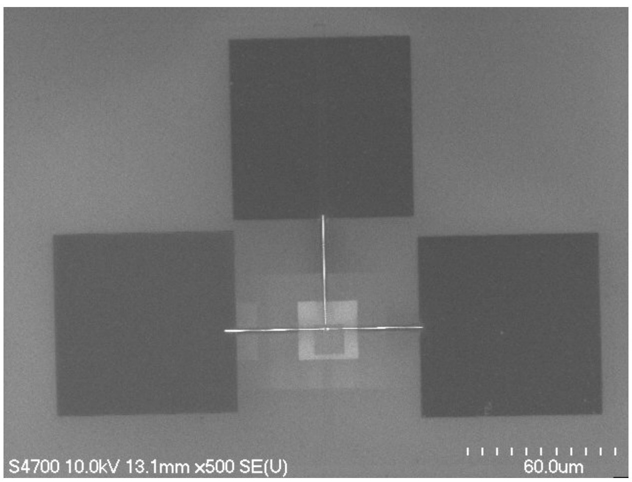

Figure 1: SEM micrograph showing the top view of the fabricated SET device, Tungsten probing pads and connecting nano leads are clearly seen, the active device is at the centre of the nano scale connecting leads.

Where the micro scaled probing pads can be clearly seen, the active area of the SET device is located at the centre of the device; the active area is connected to the micro scaled connecting pads via the nano-scaled connecting leads. The tunnel junctions for the multi dot SET system were fabricated using the chemical oxidization of tungsten nano-islands in peracetic acid which is a combination of glacial acetic acid and hydrogen peroxide in the volume ration of 1:1. Tungsten oxide is formed as a shell around the tungsten nano-islands which acts as tunnel junctions. The thickness of the tunnel oxide depends on the oxidation time used during the chemical oxidation process. The tunnel oxide thicknesses investigated for the present study had a thickness of 9±1 nm and 3± nm. After the fabrication of the tunnel junctions for the device, a 30nm Al_2O_3 passivating thin film was deposited over the device using a Perkin Elmer 2400−8J parallel plate RF sputtering system. The passivating layer of Al_2O_3 was then etched using the FIB etching technique to access the connecting pads for device characterization. The device characteristics of the SET devices were obtained using the Keithley 4200-SCS semiconductor characterization system. The individual devices with different tunnel junction widths were investigated for the Coulomb blockade characteristics. The drain current was plotted against the source drain voltage to obtain the Coulomb blockade characteristics of the SET device for different gate voltages. The differential conductances of the devices were obtained from the Coulomb blockade characteristics of the SET device, other device parameters like the tunnel resistance, tunnel capacitance, the total capacitance and the charging energy for the device were extracted form the blockade characteristics. The device parameters for different devices varying in the tunnel oxide thickness were compared. All the measurements were performed at room temperature.

III. RESULTS AND DISCUSSION

The SET device fabricated using FIB deposition technology were a multi dot SET system. It is assumed that the probable path for the electron transfer between the source and drain terminals is a linear array of conducting nano-islands. Based on the physical dimensions of the spacing between the source drain terminals and the size of the conducting nano-islands, it is estimated that there are ten conducting nan-islands between the source and drain terminals. The Coulomb blockade characteristics of the SET device having a tunnel junction thickness of 9 nm are shown in Fig. 2. The source drain voltage was swept from -4.0 V to 4.0 V. The Coulomb blockade characteristics were obtained for different gate bias of 0 V, -1.0 V and -2.0 V. The device characteristics show a clear Coulomb blockade with in the source drain voltage of -1.0 V to 1.0 V, giving the Coulomb blockade voltage of 2.0 V. The drain current was in the range of a fraction of a nano Amp. The device parameters were extracted from the *I-V* characteristics of the SET device [6─7]. For a device with thick (9 nm) tunneling oxide, the tunnel resistance was found

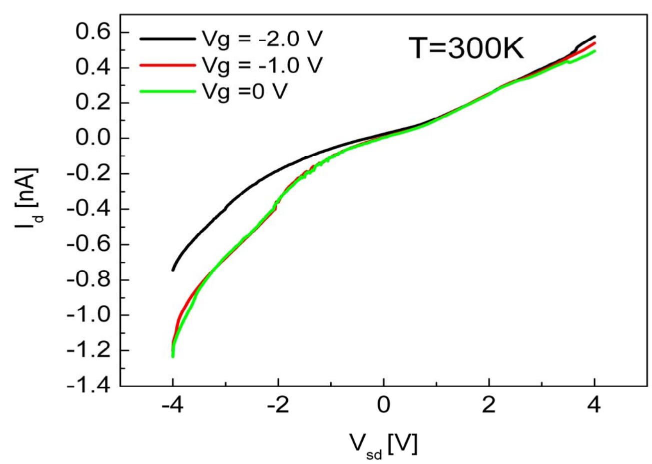

Figure 2: Non linear *I-V* characteristics of the SET device with a tunneling oxide of 9 nm.

to be 64.5 GΩ, the capacitance of individual junction was found to be 1.38 atto F, and the total capacitance of 0.728 atto F, with a charging energy of 110.0 meV. With the decrease in the thickness of the tunneling oxide (3 nm), the capacitance of the individual tunnel junctions of the device was affected and hence the total capacitance of the device was reduced. It was found that the tunnel resistance of the device decreased to a value of 35.0 GΩ, resulting in the increase in the drain current

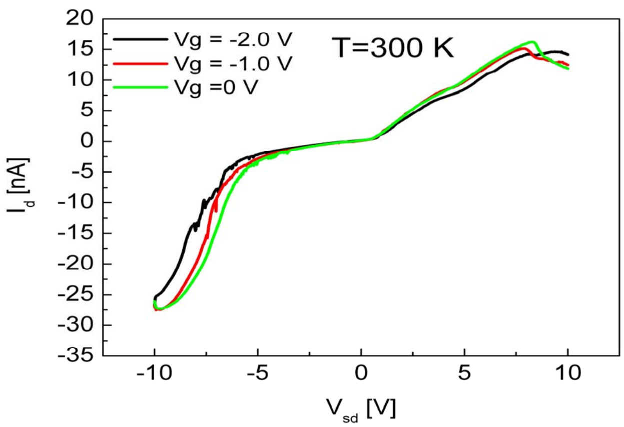

Figure 3: Non linear *I-V* characteristics of the SET device with a tunneling oxide of 3 nm.

by two orders of magnitude, increasing the Coulomb blockade voltage to 5.0 V as shown in Fig. 3, with the reduction of capacitance of the individual junction to be 1.041 atto F, with the total capacitance of 5.48 atto F. The increase in the Coulomb blockade voltage to 5.0 V indicate the reduction in the total capacitance of the device by 25%. The reduction of 25% in the total capacitance of the device from a thick oxide to a thin oxide contributes to the variation of the Coulomb blockade voltage of the device. The device characteristics show a clear Coulomb blockade, with a blockade length of 5.0 V. The Coulomb blockade characteristics were realized with a source drain sweep voltage of -10.0 V to 10.0 V. The charging energy for the device having a 3 nm thin tunnel oxide was found to be 146.0 meV. With the reduction of the thickness of

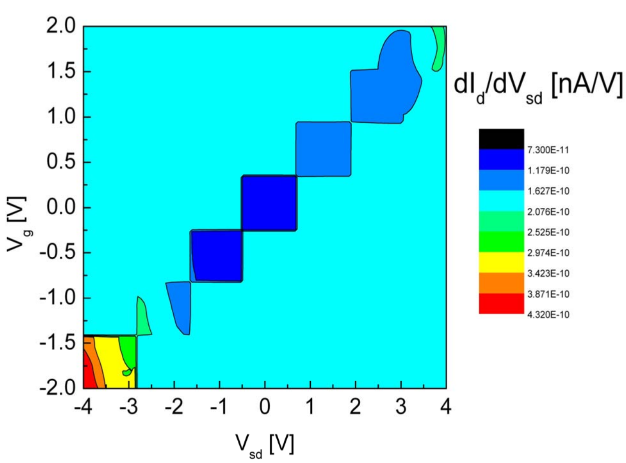

Figure 4: Contour plots showing the coulomb diamonds for a 9 nm tunneling oxide.

the tunnel oxide the charging energy of the device was increased by 33%, and the Coulomb blockade of the device was increased by 150%. With the reduction of the tunnel junction thickness, the Coulomb blockade characteristics with large blockade voltage were clearly demonstrated, resulting from the reduction of the over all capacitance of the device.

The Coulomb diamond structures, obtained from the contour plots of the differential conductance with the source-drain voltage and the gate voltage for the device with 9 nm thick tunnel oxide are shown in Fig. 4. The Coulomb diamond structure shows the variation in the differential conductance with the change in the source drain voltage and the gate voltage. The source drain voltage variation was from -4.0 V to 4.0 V, with the variation in the gate voltage of -2.0 V to 2.0 V, the differential conductance of the device varied by an order of magnitude. The coulomb diamond regions in the contour plot show the regions of stability where the transition of electron is not favorable with respect to the electrostatics of the system. The regions between the Coulomb diamonds are the regions where the transition of electron is favored [8]. The Clear variation in the blockade voltage can be seen from the Coulomb diamond structures. The Coulomb blockade voltage inferred from the Coulomb diamond was 2.0 V for the 9 nm tunnel oxide. The estimated Coulomb blockade voltage from

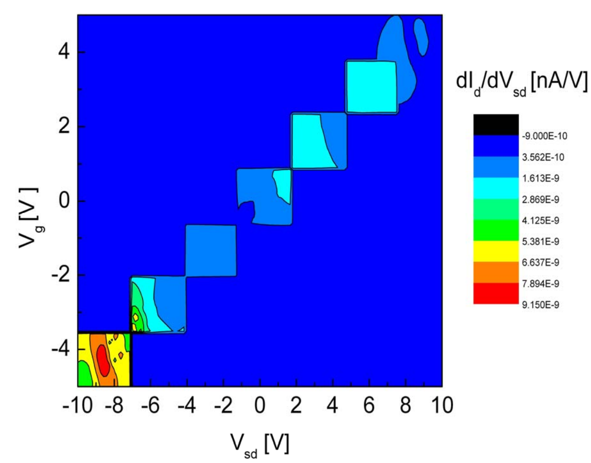

Figure 5: Contour plots showing the coulomb diamonds for a 3 nm tunneling oxide.

the total capacitance of the device including ten nano-islands between the source drain terminals was found to be 2.2 V which is in agreement with the Coulomb blockade voltage inferred from the Coulomb diamond data.

The Coulomb diamond structures, obtained from the contour plots of the differential conductance with the source-drain voltage and the gate voltage for the device with 3 nm thick tunnel oxide are shown in Fig. 5. Clear variation in the blockade voltage can be seen from the Coulomb diamond structures. The Coulomb blockade voltage inferred from the Coulomb diamond was 5.0 V for the 3 nm tunnel oxide. The differential conductance varies by an order of magnitude. The differential conductance of the device was also found to

increase with the reduction of the thickness of the tunneling oxide as shown in the Fig. 6. Reduction in the thickness of the tunnel junction decreases the tunnel resistance and increases the tunnel current. The increase in the tunnel current increases the differential conductance of the device. The differential conductance of the devices are shown for varying source drain bias, the source drain bias was varied from 0 V to 4.0 V. The differential conductance of the devices with different tunnel junction thickness showed a variation in the magnitude of the conductance, the device with a thick oxide (9 nm) showed a lower differential conductance than the device with a thin tunnel oxide (3 nm). The variation in the differential conductance was by an order of magnitude different between

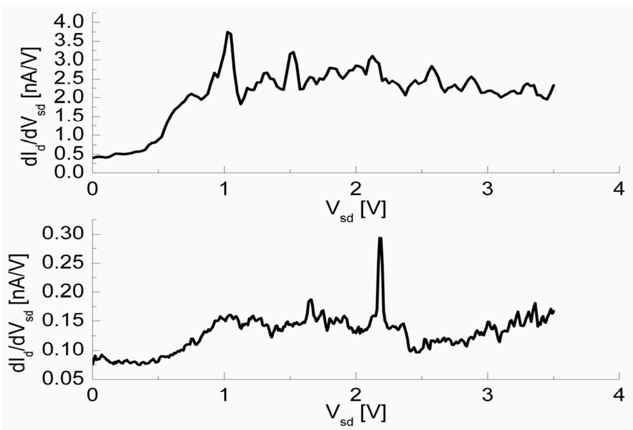

Figure 6: Comparison of the output conductance of the device with (3 nm) thin oxide (top) versus (9 nm) thick oxide (bottom).

the thick oxide and a thin oxide. The device with a thin oxide showed clean and periodic oscillations in the conductance compared to the device with the thick oxide. The differential conductance of the devices differed by an order of magnitude, the conductance of the device with 3 nm thin tunnel oxide was in the range of few nA/V. The Coulomb oscillations in the case of the device with thin oxide were preserved and it was observed that, the device with thick (9 nm) tunnel oxide the Coulomb oscillations were smeard out and the oscillations were not periodic, with lower amplitude compared to the device with a thin tunnel oxide. The variation in the tunnel oxide thickness could also be effectively utilized to vary the differential conductance of a multi dot SET system fabricated using the FIB deposition process.

IV. Conclusion

The effect of tunneling oxide thickness on the Coulomb blockade behavior of a room temperature operating multi-dot Single Electron Transistors (SET) was investigated. Room temperature operational SETs, fabricated from focused ion beam deposited tungsten nano-islands clearly show the modulation of Coulomb blockade voltage with the change in the tunnel oxide thickness. The blockade voltage of the device changes from 2.0 V to 5.0 V by the reduction of tunnel junction thickness from 9 nm to 3 nm. A decrease in the thickness of the tunneling oxide results in an increase in the conductance and tunnel current of the device by two orders of magnitude. The reduction in the thickness of the tunnel oxide from 9 nm to 3 nm resulted in 25% reduction in the total capacitance, 33% increase in the charging energy, 25% reduction in the individual capacitance, 150 % increase in the Coulomb blockade voltage. The charging energy increase from 110 meV to 146 meV. The Coulomb blockade voltage of a multi dot SET device can be increased by reducing the tunnel junction thickness. The modulation of the Coulomb blockade by changing the thickness of the tunnel junction would find applications in the nano-sensing and SET based logic.

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